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High biolability of ancient permafrost carbon upon thaw

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[1] Ongoing climate warming in the Arctic will thaw permafrost and remobilize substantial terrestrial organic carbon (OC) pools. Around a quarter of northern permafrost OC resides in Siberian Yedoma deposits, the oldest form of permafrost carbon. However, our understanding of the degradation and fate of this ancient OC in coastal and fluvial environments still remains rudimentary. Here, we show that ancient dissolved OC (DOC, >21,000 ¹⁴C years), the oldest DOC ever reported, is mobilized in stream waters draining Yedoma outcrops. Furthermore, this DOC is highly biolabile: 34 ± 0.8% was lost during a 14 day incubation under dark, oxygenated conditions at ambient river temperatures. Mixtures of Yedoma stream DOC with mainstem river and ocean waters, mimicking in situ mixing processes, also showed high DOC losses (14 days; 17 ± 0.8% to 33 ± 1.0%). This suggests that this exceptionally old DOC is among the most biolabile DOC in any previously reported contemporary river or stream in the Arctic. **Citation:** Vonk, J. E., et al. (2013), High biolability of ancient permafrost carbon upon thaw, *Geophys. Res. Lett.*, 40, 2689–2693, doi:10.1002/grl.50348.

1. Introduction

[2] The northern soil carbon (C) pool contains approximately 1672 Pg C [Tarnocai et al., 2009] of which more than a quarter (>500 Pg C) is stored in frozen Yedoma [Zimov et al., 2006] deposits in the Siberian-Arctic (Figure 1). This is approximately equal to the amount of C stored in total global forest biomass [Pan et al., 2011]. Yedoma deposits formed during the late Pleistocene [Zimov et al., 2006; Schirrmeister et al., 2011] in unglaciated Siberia and cover ca. 1 million km² (Figure 1a). Due to a lack of processing and survival of bacteria [Dutta et al., 2006; Rivkina et al., 1998] during formation, organic carbon (OC) held in

Yedoma deposits has been hypothesized to be highly biolabile upon thaw. Formation of Yedoma is initiated by accumulation of sediments [Zimov et al., 2006], and is therefore not as much exposed to repetitive freeze-thaw cycles, that process and degrade OC, in comparison to other soil ecosystems. As climate warms, permafrost soils (including Yedoma) will thaw and decompose leading to the production of greenhouse gases, in turn accelerating climate warming [Dutta et al., 2006; Schaefer et al., 2011]. This is referred to as the “permafrost carbon feedback” (PCF). Initial estimates suggest that the PCF can be substantial [Zimov et al., 2006; Schuur et al., 2008; Schaefer et al., 2011], but remarkably, this process is not included in any Intergovernmental Panel on Climate Change (IPCC) [IPCC, 2007] scenario of future climate change. Understanding how frozen OC pools are processed upon thaw is therefore crucial for understanding future climate change and C dynamics in the Arctic and globally.

[3] Four physical mechanisms release OC from permafrost to the atmosphere [Schuur et al., 2008]: active layer deepening, talik formation, thermokarst development, and erosion. Coastal and riverbank erosion of Yedoma deposits can occur over vast distances (e.g., along the >5000 km East Siberian Arctic coastline) [Vonk et al., 2012] and may release OC from entire soil depth profiles (up to ca. 40 m) directly to aquatic environments. A deepening of the active layer—the seasonally thawed surface soil, may also lead to an increased supply of permafrost derived OC to inland waters over regional scales. After thawing, the crucial current unknowns are how much, and how rapidly does OC held within these deposits enter the contemporary C cycle. Inland and coastal waters are increasingly recognized as important processors of terrestrial organic carbon (OC), generating a substantial flux of CO₂ to the atmosphere [Aufdenkampe et al., 2011; Battin et al., 2008; Bianchi, 2011]. Carbon processing during coastal release in the Siberian Arctic has been shown to be substantial [Alling et al., 2010; Sánchez-García et al., 2011]. This study investigates the “hydrological biolability”, i.e., the potential biodegradability within the residence time of the aquatic system, of OC from recently thawed Yedoma deposits introduced to aquatic ecosystems.

[4] The “Duvannyi Yar” exposure on the banks of Kolyma River in Northeast Siberia (Figure 1) is a classical and relatively well-studied Yedoma site [e.g., Vasil’chuk and Vasil’chuk, 1997; Dutta et al., 2006]. Radiocarbon ages of the ca. 40 m high deposits range between 13,000 and 45,000 years [Vasil’chuk and Vasil’chuk, 1997]. Permafrost thaw and/or riverbank erosion result in mean retreat rates of 3–5 m/yr. Water from melting ice wedges feed streams that carry recently thawed Yedoma off the cliff into the Kolyma River (Figure 2). These sediment-laden, first-order streams represent an integrated signal of recently thawed Yedoma.

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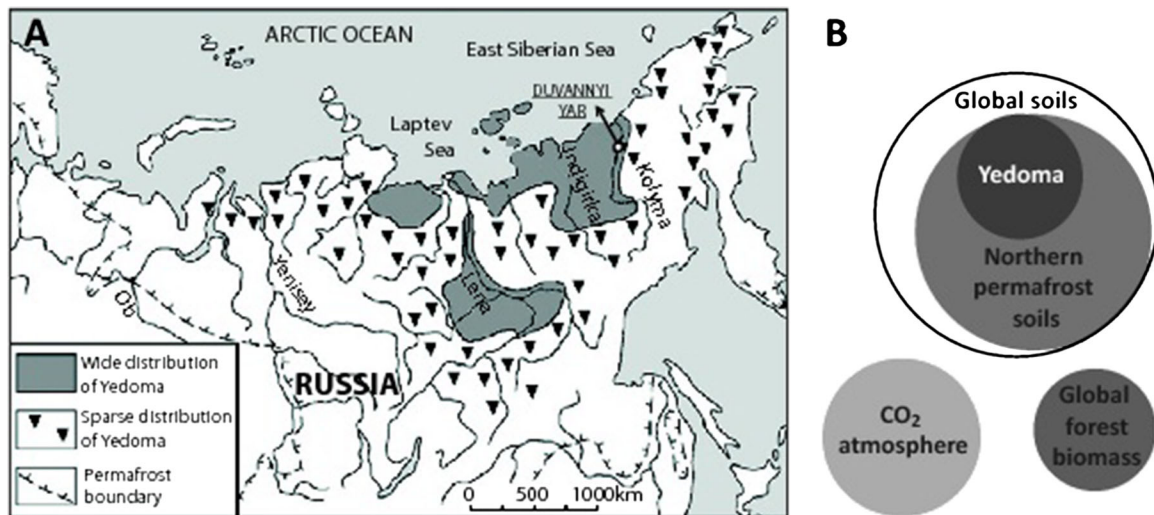


Figure 1. (a) Yedoma extent in the Siberian Arctic [Romanovskii, 1993], overlain with major rivers and our study site Duvanniy Yar. (b) Relative carbon pool sizes of Yedoma (500 Pg) [Zimov *et al.*, 2006; Tarnocai *et al.*, 2009] in comparison with other major global carbon pools (global soils 2400 Pg, northern permafrost soils 1672 Pg, global forest biomass 450 Pg and atmospheric CO₂ 750 Pg) [IPCC, 2007; Tarnocai *et al.*, 2009; Pan *et al.*, 2011].

These first-order streams are formed early in the summer when ice wedges start to melt, and their course and magnitude depends on local riverbank collapse, thaw rates and relief. We used the stream dissolved OC (DOC) for incubations and mixing experiments with Kolyma River and East Siberian Sea-water (see section 2), with the goal to estimate biolability during fluvial and coastal processing of ancient permafrost OC.

2. Methods

[s] In July 2010, we sampled six thaw streams along the Duvanniy Yar exposure (on a line from 68.631°N–159.156°E

to 68.631°N–159.143°E, Figure 2) on the Kolyma River. The streams have all freshly formed from thawing ice-rich Yedoma permafrost, and meander down the cliff in a course that is dependent on local bank collapse, thaw rates and relief. Estimated flow rates on our sampling day were ca. 2.5–10 L/s, stream temperatures just above 0 °C and transport time from thaw to entry into Kolyma River < 1 h. The water was filtered through precombusted 0.7 µm glass fiber filters (Whatman) and analyzed at the Northeast Science Station in Cherskii (Russia), for DOC on a Shimadzu TOC-V analyzer using established protocols [Mann *et al.*, 2012]. Frozen water samples were exported, acidified (to remove inorganic carbon)

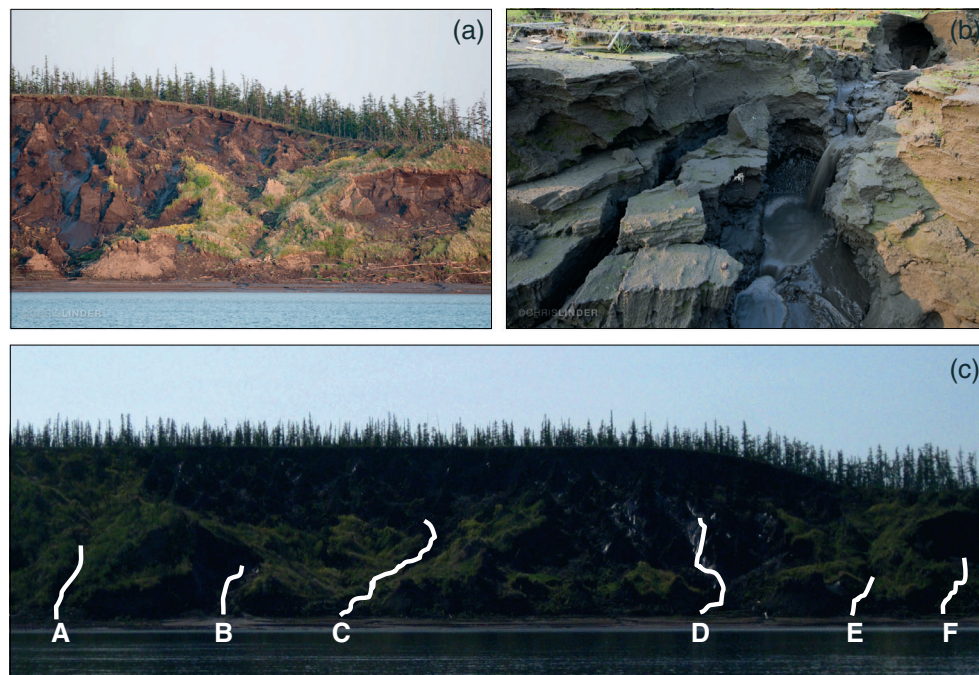


Figure 2. (a) Duvanniy Yar exposure on the Kolyma river bank containing (b) freshly thawed Yedoma organic matter is exported down the cliffs merging in mud streams that drain into Kolyma River. (c) Location of thaw streams sampled in 2010. (photos © Chris Linder).

and analyzed for ^{14}C -DOC at the U.S. National Ocean Sciences Accelerator Mass Spectrometry facility of the Woods Hole Oceanographic Institution (USA). Frozen particulate matter samples were acidified (to remove inorganic carbon) and analyzed for percent OC at the Stable Isotope Laboratory at the Department of Geological Sciences at Stockholm University (Sweden) and for ^{14}C -POC at the AMS facility of the Laboratory of Ion Beam Physics of the Swiss Federal Institute of Technology (Zürich, Switzerland). In July 2011, we returned to Duvannyi Yar and collected a composite sample of four thaw streams (approximate locations of the streams B, C, D, F in 2010, Figure 2c). The samples were kept cool during transport back to the Northeast Science station and filtered (pre-combusted GF/F 0.7 μm , Whatman). The same day, we prepared 0.5%, 1.0% and 10% dilutions of Duvannyi Yar water with Kolyma River water and East Siberian Sea water (also filtered through pre-combusted 0.7 μm GF/F, no inoculum added [Holmes *et al.*, 2008; Mann *et al.*, 2012]). The dilutions were distributed into 40 mL pre-combusted glass vials (in triplicate). All vials, along with the control samples (filtered Kolyma River, East Siberian Sea and Duvannyi Yar water) were positioned on a shaker table and left to incubate at room temperature (ca. 20°C). This is circa 4° warmer than the average July surface water temperature of Kolyma River (16.3°C, SD=0.66, $n=27$; www.thepolarisproject.org/data/, <http://arcticgreatrivers.org/data.html>). The incubations were kept in dark, oxygenated conditions (capped loosely) for 14 and 28 days, to determine the bioavailable DOC (BDOC). At $T=14$ and $T=28$ days, the bottles were acidified to pH 2 and OC loss was measured directly from the vials. No flocculation was observed during the incubations or prior to analyses.

3. Results and Discussion

[6] Yedoma thaw streams of Duvannyi Yar ($n=6$; 2010) carried exceptional amounts of suspended sediments (552 ± 69 g/L; mean \pm SD; Table 1), with high dissolved OC (DOC) and particulate OC (POC) concentrations (196 ± 71 mg/L and 7970 ± 100 mg/L, respectively; Table 1). The following summer, a composite stream sample taken in July 2011 from four thaw streams (see section 2) contained 155 mg/L DOC. Studies on Arctic river DOC generally report modern ages [Neff *et al.*, 2006; Guo and Macdonald, 2006; Raymond *et al.*, 2007]. Duvannyi Yar stream waters, by contrast, contained DOC far older than ever previously reported in natural waters anywhere (2010: $-946 \pm 25\%$ or 24,100 \pm 3900 years, 2011: -933% or 21,700 years; Table 1). Ages of POC were comparable (2010: $-953 \pm 36\%$ or 27,500 \pm 8200 years; Table 1) to DOC ages. Stable C isotopic values of DOC and POC pools were also similar (DOC $-25.7 \pm 0.28\%$, POC $-25.1 \pm 0.31\%$; Table 1), further confirming a common source, and resembling Yedoma soil $\delta^{13}\text{C}$ values (-26.3% , SD=0.67‰, $n=374$) [Schirmer *et al.*, 2011; Vonk *et al.*, 2012]. Finally, deuterium and oxygen isotope analyses on the 2011 composite stream water (-246% and -32.4% , respectively) were similar to a local ice wedge sample (-256% and -33.4% , respectively) and to previously reported Yedoma ice wedge values [Meyer *et al.*, 2002], indicating that the thaw streams originated predominantly in Pleistocene deposits, and not from recent precipitation (rain $\delta^{18}\text{O}$ -16.3% , $\delta^2\text{H}$ ca. -101% ; snow $\delta^{18}\text{O}$ -26.2% , $\delta^2\text{H}$ ca. -199%) or river water ($\delta^{18}\text{O}$ ca. -22% ; $\delta^2\text{H}$ -175%) [Meyer *et al.*, 2002; Welp *et al.*, 2005].

Table 1. Bulk Geochemical Parameters of Duvannyi Yar Thaw Streams in 2010 and 2011

Sampling date	#	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{D}$ (‰)	DOC				POC				SPM g/L
				(mg/L)	$\delta^{13}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	^{14}C age (years)	(mg/L)	$\delta^{13}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	^{14}C age (years)	
2010												
27 Jul 2010	A	—	—	154	-25.6	-974 ± 1.2	29400 ± 380	8580 ± 530	-24.9 ± 0.04	-988 ± 0.73	35800 ± 500	608 ± 53
27 Jul 2010	B	—	—	336	-26.1	-951 ± 1.3	24200 ± 230	8480 ± 590	-25.7 ± 0.03	-992 ± 0.77	38300 ± 730	609 ± 16
27 Jul 2010	C	—	—	194	-25.9	-911 ± 0.76	19350 ± 70	9240 ± 440	-25.2 ± 0.05	-920 ± 1.0	20200 ± 100	628 ± 16
27 Jul 2010	D	—	—	176	-26.0	-970 ± 0.49	28000 ± 130	6700 ± 820	-25.1 ± 0.1	-974 ± 0.79	29210 ± 240	494 ± 13
27 Jul 2010	E	—	—	161	-25.3	-926 ± 1.1	20900 ± 130	6920 ± 300	-24.8 ± 0.08	-939 ± 0.78	22380 ± 100	491 ± 6.7
27 Jul 2010	F	—	—	154	-25.7	-943 ± 1.2	22900 ± 170	7880 ± 2000	-25.1	-907 ± 1.2	19070 ± 100	484 ± 9.5
2011												
22 Jul 2011	Comp	-32.4 ± 0.04	-246 ± 0.65	155 ± 2.4	-25.47	-933 ± 0.62	21700 ± 85	—	-25.2 ± 0.21	—	—	—

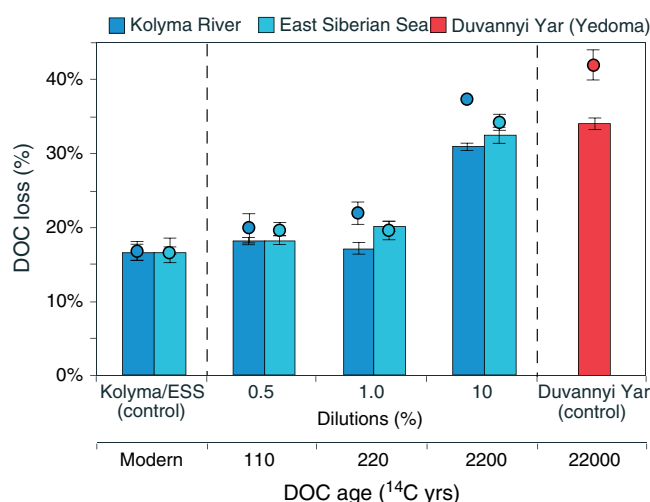


Figure 3. Dissolved organic carbon loss (%) after 14 days (bars) and 28 days (points) dark incubations at 20°C for Kolyma River (light blue), East Siberian Sea (dark blue), Yedoma streams (red), and three dilutions of Yedoma water with Kolyma River or East Siberian Sea water. The ^{14}C age of DOC (years) (x-axis) represents the proportion of Duvanniy Yar (Yedoma) stream water added to Kolyma River or East Siberian Sea water. Standard deviations represent errors from triplicate experiments.

[7] Our biolability study focused on DOC instead of POC, because it is the most important intermediary in the global C cycle. Only low-molecular weight dissolved compounds can be transported through microbial cell membranes, and are thus readily available for microbial metabolism [Battin *et al.*, 2008]. Thaw streams originating in Pleistocene Yedoma deposits lost $34 \pm 0.8\%$ of their DOC after 14 days and $41 \pm 3\%$ after 28 days incubation (see section 2 and Figure 3). With an initial DOC concentration of 155 mg/L, these losses convert to a remarkable decrease in DOC concentration of 52 mg/L in 14 days, or 63 mg/L in 28 days. Additionally, samples of Kolyma River and East Siberian Sea water (salinity 26) that were spiked with Yedoma-DOC showed an increase in DOC loss with increasing Yedoma additions (Figure 3), from ca. 18% loss for a 0.5% Yedoma addition to ca. 32% loss for a 10% Yedoma addition after 14 days. Higher percent OC losses were observed in both fresh and saline waters with increasing additions of Yedoma OC (Figure 3) suggesting that Yedoma OC may enhance, or even prime, remineralization of contemporary DOC [Bianchi, 2011]. We propose that the high biolability of this >21,000 year old DOC can be explained by the following: (i) a lack of pre-processing of DOC prior to thaw [e.g., Dutta *et al.*, 2006], (ii) the presence of more low-molecular-weight compounds or fewer aromatics [Waldrop *et al.*, 2010], (iii) nutrient availability, and (iv) an abrupt spike in the activity of Yedoma's intrinsic bacteria, having survived for thousands of years [Rivkina *et al.*, 1998], but now exposed to temperatures above zero and availability of (liquid) water. Previous reports on Arctic stream or river biolability report percent DOC losses up to 42% (3 months at 20°C; Alaska) [Holmes *et al.*, 2008], up to 35% (40 days at 25°C; Alaska) [Balcarczyk *et al.*, 2009], up to 53% for under-ice waters (28 days, 15°C; Alaska) [Wickland *et al.*, 2012], up to 28% (97 days, temperature not given; W-Siberia) [Kawahigashi *et al.*, 2004], and up

to 20% (28 days, room temperature; Kolyma River) [Mann *et al.*, 2012]. Variable incubation conditions make direct comparisons challenging, yet a 34% loss of ancient (>21,000 ^{14}C years) DOC after only 14 days is among the highest ever reported for pristine, non-glacier-fed, rivers or streams.

[8] The conventional way to calculate and globally-upscale greenhouse gas release fluxes from thawing permafrost is typically based on direct CO_2 and CH_4 emission measurements from thawing tundra soils [Dorrepaal *et al.*, 2009]. Here, we show that a substantial portion of greenhouse gases may be generated during stream, river and shelf transport. One should note here that we only examined release of Yedoma OC in the dissolved phase; the dynamics of POC, with fluxes that are likely orders of magnitude higher (Table 1), and that may breakdown (also photochemically) to release substantial amounts of DOC, remain undetermined. Our results further indicate that differences in the reactivity of contemporary versus old OC, and associated fluxes need to be accounted for in future studies. The strong degradation of Yedoma-DOC in the stream network could also explain why significant seasonal DOC aging in the Kolyma River main-stem has not been observed [Neff *et al.*, 2006]. Increased contributions of permafrost-derived C may not be easy to detect at the mouth of large Arctic rivers as it is removed rapidly over short incubation times likely comparable to water residence times within the headwaters (~3–7 days from Duvanniy Yar to river mouth, assuming average river velocities of 0.5–1.5 m/s, Holmes *et al.* [2012]). Furthermore, the flux of terrestrial-derived OC to the Arctic Ocean, estimated from measurement at the river mouth, may misrepresent the actual mobilization and turnover of the DOC in the watershed, as processing of DOC within the catchment, prior to arrival at the river mouth is not included in these estimates. Similar to recent studies that revealed the presence of biolabile ancient OC being liberated from glaciers [Hood *et al.*, 2009], our data also contrasts to the prevailing paradigm of age versus reactivity of OC.

4. Conclusions

[9] We show here that Yedoma DOC, with >21,000 ^{14}C years the oldest ever reported, is highly biolabile upon release, both in fluvial (i.e., Kolyma River) and in coastal environments (i.e., East Siberian Sea) (Figure 3). Estimates of the exact contribution of Yedoma OC in Arctic C cycling are improving [Vonk *et al.*, 2012], but are still subject to considerable uncertainties, e.g., due to a lack of adequate spatial coverage of Yedoma deposits [Romanovskii, 1993], and accurate estimates of delta and riverbank erosion. Ongoing Arctic climate warming is expected to further increase the thermal exposure, thaw and erosion of Yedoma, particularly along the extensive East Siberian Arctic coastline, where Yedoma deposits are ubiquitously present and increasingly exposed to wave fetch and storms due to recent reductions in sea ice [IPCC, 2007; Stroeve *et al.*, 2007]. Yedoma OC, hosting ca. 25% of the total belowground permafrost soil OC [Zimov *et al.*, 2006; Tarnocai *et al.*, 2009] is very old, yet highly biologically reactive upon mobilization. The high biolability of this material seems likely to amplify the effect of the PCF scenario in the Arctic. Furthermore, examining permafrost degradation through ^{14}C -DOC measurements at river mouths may not be representative for the actual mobilization and turnover of permafrost C, as extensive

processing of permafrost derived-C *within* the watershed may be masking the river mouth signal. It is apparent that further studies are needed to address the magnitude of the flux of thawing Yedoma OC, but also, importantly, to incorporate the reactivity of this material in regional and global C budgets.

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References

- Alling, V., et al. (2010), Nonconservative behavior of dissolved organic carbon across the Laptev and East Siberian seas, *Global Biogeochem. Cycles*, **24**, GB4033, doi:10.1029/2010GB003834.
- Aufdenkampe, A. K., et al. (2011), Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere, *Front. Ecol. Environ.*, **9**, 53–60, doi:10.1890/100014.
- Balcarczyk, K. L., J. B. Jones Jr., R. Jaffé, and N. Maie (2009), Stream dissolved organic matter availability and composition in watersheds underlain with discontinuous permafrost, *Biogeochem.*, **94**, 255–270, doi:10.1007/s10533-009-9324-x.
- Battin, T. J., et al. (2008), Biophysical controls on organic carbon fluxes in fluvial networks, *Nat. Geosci.*, **1**, 95–100, doi:10.1038/ngeo101.
- Bianchi, T. S. (2011), The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect, *Proc. Natl. Acad. Sci. USA*, doi:10.1073/pnas.1017982108.
- Dorrepaal, E., et al. (2009), Carbon respiration from subsurface peat accelerated by climate warming in the subarctic, *Nature*, **460**, 616–619, doi:10.1038/nature08216.
- Dutta, K., E. A. G. Schuur, J. C. Neff, and S. A. Zimov (2006), Potential carbon release from permafrost soils of Northeastern Siberia, *Glob. Change Biol.*, **12**, 2336–2351, doi:10.1111/j.1365-2486.2006.01259.X.
- Guo, L., and R. W. Macdonald (2006), Source and transport of terrigenous organic matter in the upper Yukon River: Evidence from isotope ($\delta^{13}\text{C}$, $\Delta^{14}\text{C}$, and $\delta^{15}\text{N}$) composition of dissolved, colloidal, and particulate phases, *Global Biogeochem. Cycles*, **20**, GB2011, doi:10.1029/2005GB002593.
- Holmes, R. M., et al. (2008), Lability of DOC transported by Alaskan rivers to the Arctic Ocean, *Geophys. Res. Lett.*, **35**, L03402, doi:10.1029/2007GL032837.
- Holmes, R. M., et al. (2012), Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas, *Estuaries Coasts*, doi:10.1007/s12237-011-9386-6.
- Hood, E., et al. (2009), Glaciers as a source of ancient and labile organic matter to the marine environment, *Nature*, **462**, 1044–1048, doi:10.1038/nature08580.
- Intergovernmental Panel on Climate Change (IPCC) (2007), *The Scientific Basis*, Cambridge Univ. Press, New York.
- Kawahigashi, M., K. Kaiser, K. Kalbitz, A. Rodionov, and G. Guggenberger (2004), Dissolved organic matter in small streams along a gradient from discontinuous to continuous permafrost, *Glob. Change Biol.*, **10**, 1576–1586, doi:10.1111/j.1365-2486.2004.00827.x.
- Mann, P. J., et al. (2012), Controls on the composition and lability of dissolved organic matter in Siberia's Kolyma River basin, *J. Geophys. Res.*, **117**, G01028, doi:10.1029/2011JG001798.
- Meyer, H., A. Dereviagin, C. Siegert, L. Schirrmeister, and H.-W. Hubberten (2002), Palaeoclimate reconstruction on Big Lyakhovsky Island, North Siberia—Hydrogen and oxygen isotopes in ice wedges, *Permafrost Periglac.*, **13**, 91–105, doi:10.1002/ppp.416.
- Neff, J., et al. (2006), Seasonal changes in the age and structure of dissolved organic carbon in Siberian rivers and streams, *Geophys. Res. Lett.*, **33**, L23401, doi:10.1029/2006GL028222.
- Pan, Y., et al. (2011), A large and persistent carbon sink in the world's forests, *Science*, **333**, 988–993, doi:10.1126/science.1201609.
- Raymond, P., et al. (2007), Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest arctic rivers, *Global Biogeochem. Cycles*, **21**, GB4011, doi:10.1029/2007GB002934.
- Rivkina, E., D. Gilichinsky, S. Wagener, J. Tiedje, and J. McGrath (1998), Biogeochemical activity of anaerobic microorganisms from buried permafrost sediments, *Geomicrobiol. J.*, **15**, 187–193, doi:10.1080/01490459809378075.
- Romanovskii, N. N. (1993), *Fundamentals of the Cryogenesis of the Lithosphere*, University Press, Moscow, pp. 336.
- Sánchez-García, L., et al. (2011), Inventories and behavior of particulate organic carbon in the Laptev and East Siberian seas, *Global Biogeochem. Cycles*, **25**, GB2007, doi:10.1029/2010GB003862.
- Schaefer, K., T. Zhang, L. Bruhwiler, and A. P. Barrett (2011), Amount and timing of permafrost carbon release in response to climate warming, *Tellus*, **63B**, 165–180, doi:10.1111/j.1600-0889.2011.00527.X.
- Schirrmeister, L., et al. (2011), Sedimentary characteristics and origin of the Late Pleistocene Ice Complex on north-east Siberian Arctic coastal lowlands and islands—A review, *Quatern. Int.*, **241**, 3–25, doi:10.1029/2011JG001647.
- Schuur, E. A. G., et al. (2008), Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle, *Bioscience*, **58**, 701–714, doi:10.1641/B580807.
- Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, **34**, L09501, doi:10.1029/2007GL029703.
- Tarnocai, C., et al. (2009), Soil organic carbon pools in the northern circumpolar permafrost region, *Global Biogeochem. Cycles*, **23**, GB2023, doi:10.1029/2008GB003327.
- Vasil'chuk, Y. K., and A. C. Vasil'chuk (1997), Radiocarbon dating and oxygen isotope variations in Late Pleistocene syngenetic ice wedges, Northern Siberia, *Permafrost Periglac.*, **8**, 335–345, doi:10.1002/(SICI)1099-1530(199709)8:3<335::AID-PPP259>3.0.CO;2-V.
- Vonk, J. E., et al. (2012), Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia, *Nature*, **489**, 137–140, doi:10.1038/nature11392.
- Waldrop, M. P., K. P. Wickland, R. III White, A. A. Berhe, J. W. Harden, and V. E. Romanovsky (2010), Molecular investigations into a globally important carbon pool: Permafrost-protected carbon in Alaskan soils, *Glob. Change Biol.*, **16**, 2543–2554.
- Welp, L. R., et al. (2005), A high-resolution time series of oxygen isotopes from the Kolyma River: Implications for the seasonal dynamics of discharge and basin-scale water use, *Geophys. Res. Lett.*, **32**, L14401, doi:10.1029/2005GL022857.
- Wickland, K. P., et al. (2012), Biodegradability of dissolved organic carbon in the Yukon River and its tributaries: Seasonality and importance of inorganic nitrogen, *Global Biogeochem. Cycles*, **26**, GB0E03, doi:10.1029/2012GB004342.
- Zimov, S. A., E. A. G. Schuur, and F. S. III Chapin (2006), Permafrost and the global carbon budget, *Science*, **312**, 1612–1613, doi:10.1126/science.1128908.